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Jørgensen, Anders Michael; Clausen, Thomas; Leistiko, Otto

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NOVEL LIGHT TRAPPING SCHEME FOR THIN CRYSTALLINE CELLS UTILIZING DEEP STRUCTURES ON BOTH WAFER SIDES

Anders M. Jorgensen, Thomas Clausen and Otto Leistiko
Microelectronics Centre, Build. 345E, Technical University of Denmark DK-2800 Lyngby, Denmark.

ABSTRACT

A new light trapping structure is presented with trapping capabilities comparable to or better than those of the perpendicular grooves structure. The new structure traps a larger fraction of rays for 8-80 passes than the perpendicular grooves structure. The average path length enhancement is about 62 times the average thickness. The structure consists of deep (~200μm) inverted pyramids on the front side and deep (~200μm) truncated pyramids with eight sides on the back. The structure is realized in crystalline silicon by wet chemical etching using potassium hydroxide (KOH) and isopropanol (IPA).

A process for creating thin solar cells with this light trapping scheme is described. The process includes only two main photolithographic steps and features a selfaligned front metallization. The process uses 250μm wafers to create cells that on average are about 70μm thick.

INTRODUCTION

We propose a new cell design with deep pyramidal structures on both wafer sides (Fig. 1). On the illuminated side there are deep inverted pyramids. On the backside there are many-sided pyramids. We will refer to this cell design as "octagon". The main advantages of this design is that very efficient light trapping is achieved and furthermore it requires only two photolithographic masks. The deep front structures allow use of a selfaligned proces for frontside metallization. The deep etching reduces the volume of bulk material considerably and therefore the requirement of high minority carrier lifetime in the bulk can be relaxed [1], [2].

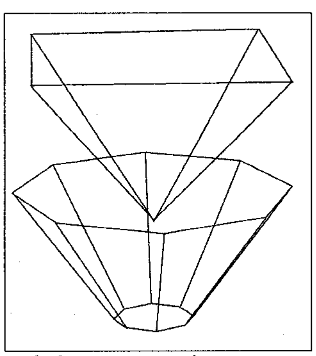

Fig. 1. Sketch of the proposed octagon structure. With inverted pyramid on top and an eight sided pyramid at the bottom. The depths of the pyramids are about 200μm.

EXPERIMENTAL SETUP

The KOH, IPA etching system used at the Microelectronics Centre (MIC) has a closed thermostatted vessel and a reflux condenser. A pump maintains a flow from bottom to top. The etchant is stored in a tank and the density is measured and adjusted with water every time the etchant is used. The density is adjusted to give a concentration of 28% by weight. During etching there is a separate phase of IPA covering the surface which assures saturation of IPA. The IPA phase can be maintained during long etches by carefully adding IPA while the etchant is warm. The etch rates in the main crystallographic directions in microns per minute at 70°C are 0.66±0.02 for (100), 0.19±0.01 for (110) and 0.012±0.001 for (111).

FABRICATION

An experiment was made with moderately doped 7-20 Ωcm p-type 350μm thick wafers. A thin dry thermal oxide was grown (~300Å). In a LPCVD furnace a silicon rich silicon nitride was deposited (~1800Å). One test mask was transferred to both sides using RIE. One side as a positive masking the other negative. The mask has 360x360μm squares arranged in a brickwork pattern with 30μm gridlines. The wafers were etched in KOH, IPA at 70°C until the inverted pyramids were completely etched (Fig. 2).

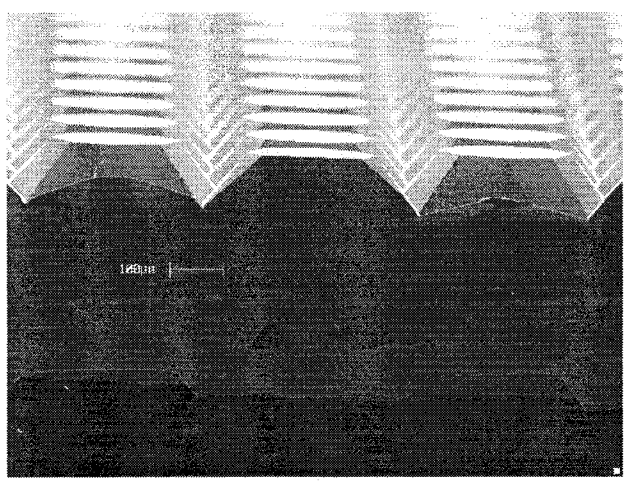

Fig. 2. A cross sectional view of the structure showing the octagons on the top and the inverted pyramids at the bottom. Etched in KOH, IPA at 70°C.

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The backside octagon is shown in Fig. 3. The eight sided pyramid is quite regular and the angle between the planes is 135°±0.7°. This angle is quite surprising and does not correspond to any given in the litterature [3], [4].

Some (111) planes can be seen on the etched pyramids (Fig. 3). These leftover planes will make the light trapping less efficient because some light will be coupled out after only a few passes as in [2]. On these samples the width of the octagon is about 200µm. They can be made smaller by using an apropiately smaller mask. Our goal on the 260µm structures is to have a final octagon width of 40µm. The brickwork pattern makes the area covered by (111) planes larger. To counter this our new design has a regular chess board pattern.

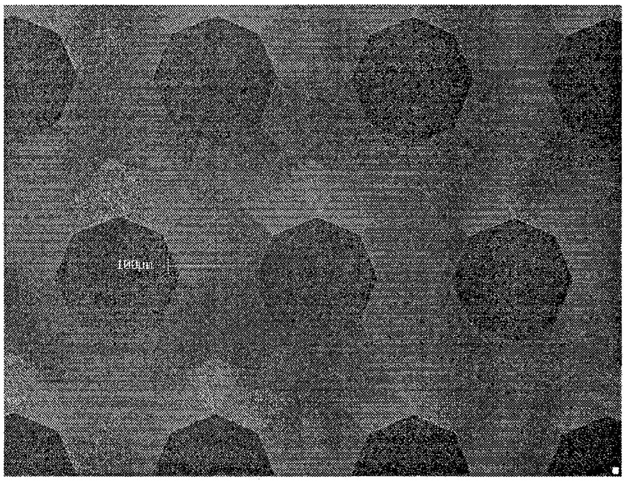

Fig. 3. SEM micrograph of the octagons. The flat is aligned along the top of the picture. Note that parts of (111) planes can be seen. Etched in KOH, IPA at 70°C.

The undercut etchrate was measured by etching a sample for 100 min. Then taking a SEM micrograph. Then etching for another 100 min and taking another micrograph. The distance between two parallel planes on the octagon were measured. These measurements were compared with the (100) etch depth to give a ratio between the (100) etch rate and the under cut etch rate. This ratio was about 1.9±0.1.

OPTICAL PERFORMANCE

This cell design has efficient light trapping because the bottom pyramid scatters normally incident light away from the plane of incidence. This means that, in general, a normally incident ray will travel in all three dimensions inside the crystal. This is in contrast to most one-sided geometrical light trapping structures where the ray only travels in the plane of incidence.

Raytracing program

A program was made to quantify the light trapping capabilities of the structure. The program can analyze structures with an arbitrary number of planes with any number of corners. It traces a ray until it completely escapes. For a ray striking a surface with an angle less than the critical angle the reflection probability is calculated. In order to simulate unpolarized light the Fresnel expressions for reflection of p or s polarization is given equal weight:

$$R(\theta_i,\theta_t)=\frac{1}{2}\left(\frac{\tan^2(\theta_i-\theta_t)}{\tan^2(\theta_i+\theta_t)}+\frac{\sin^2(\theta_i-\theta_t)}{\sin^2(\theta_i+\theta_t)}\right) \quad (1)$$

Here θ_i is the angle of incidence and θ_t is the angle of the transmitted ray. The transmission angle is found from Snells law.

The program calculates the total length a beam travels inside the structure. This length is compared with the average structure thickness to give the length enhancement factor (LEF) also called length boost [1]. The program traces a number of rays and calculates the individual LEF. It also calculates the average of all the traced rays called ALEF.

Simulations

Three structures were implemented and compared (Table 1). Unity reflectance is assumed on all surfaces except the top inverted pyramid or groove. This means that the beams on the top cause a shading loss. This shading loss is 8% on all the structures. This loss has been removed from the calculations. The beamwidth in the calculation is used because the octagon structure requires it for metallization.

Structure	Side-length	Beam width	ALEF
Inverted pyramids	260µm	11.0µm	44
Perpendicular grooves	135µm	10.8µm	62
Octagon	260µm	11.0µm	62

Table 1 The parameters used for the simulation. The sidelength is the sidelength of the pyramids for the inverted pyramid and octagon. The sidelength for the perpendicular grooves is the groove width. The average length enhancement factor (ALEF) gives the total length travelled by an average ray inside the structure.The width of the bottom octagon is 40µm.

The average thickness was found by sampling the structure thickness at 40,000 evenly placed points and then generating the average. All the structures have an average thickness of 168.2µm. This average thickness corresponds to the thickness of the octagon structure when fabricated on 350µm thick wafers.

The length enhancement of the individual rays is shown in Fig. 4. As can be seen the octagon and the perpendicular grooves are comparable although the octagon structure has a somewhat higher percentage of rays remaining for LEF values of 8-80. The perpendicular groove structure has the same average as the octagon because a larger fraction of the light is trapped for extremely long passes.

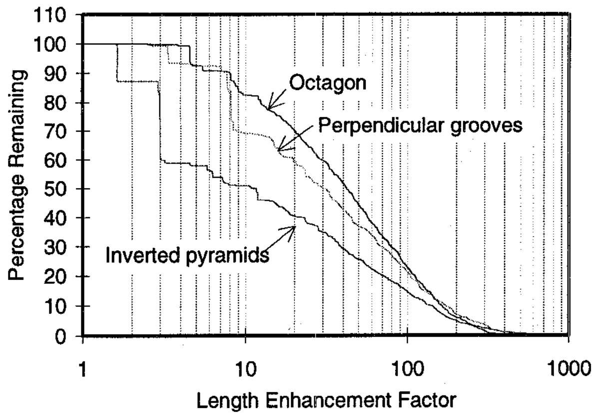

Fig. 4. The length enhancement factor for two often used light trapping structures compared with the octagonal structure (1000 rays). The data used are given in Table 1. Ideal reflectors are assumed everywhere except on the top structures.

As mentioned by *Campbell et. al.* [1] the really interesting number for solar cell purposes is not the average length enhancement factor. The shortcircuit current is of more interest. It is given by a convolution of Fig. 4 and the absorption probability of silicon weighted with the intensity spectrum. The absorption probability is exponential by nature and a larger fraction of the light is trapped for LEF's up to 80 for the octagon than for the perpendicular grooves. Therefore we conclude that the short circuit current will be higher for the octagon structure than for the perpendicular grooves structure. It should be noted that it is only for a scheme with beams as the one we suggest that this comparison holds. As for perpendicular groove cells with shallow angle metallization no easy comparison can be made.

DISCUSSION

We have shown that the light trapping scheme can be implemented in silicon by wet etching. The etched structure will behave worse than the theoretical calculations because of loss due to the (111) planes left. However the efficiency of such cells should still be high. This makes it interesting to actually fabricate cells. A fabricated cell is expected to resemble the one shown in Fig. 5.

Front beam underetch

For very deep etches of holes the final shape is determined by the planes with the lowest etchrate. In case of the inverted front pyramids they are determined by the (111) planes. However the beams defining the hole becomes underetched. Two major factors are responsible for this underetch. The first is the etchrate of the (111) plane. This underetch will account for an underetch of about 4.5µm for a side length of 260µm. This underetch would be the same on both sides of the beam. The other factor is the misalignment of the mask with respect to the crystallographic directions. For a standard wafer the flat misalignment is typically ±1° [5]. If one assumes a misalignment of 1° this leads to an underetch of about 4.5µm for a side length of 260µm. This misalignment underetch would only show on one side of the beam. The effect of this misalignment becomes more severe as the feature size increases. Especially for v-grooves the effect can be disastrous leading to an underetch of about 170µm for a 1 cm long groove.

The final width of the beam is what defines our front metal grid and, thus, our shading loss. Because of this it is unacceptable to have some random flat misalingment. We have decided to use an alignment fork [5] to find the crystallographic directions precisely. Using this fork we can take advantage of the misalignment undercut to control the shading loss. On our new masks we can control the shading loss from about 4% to about 16%.

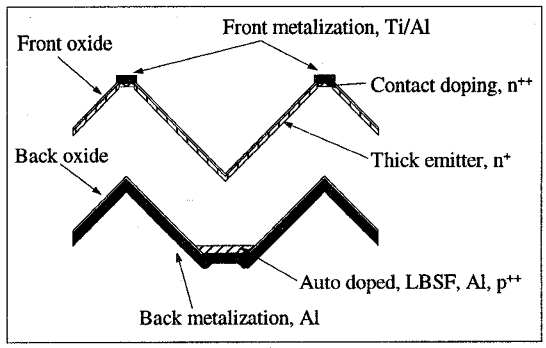

Fig. 5. Cross sectional view of one possible cell. The sketch shows the two sides as parallel for sake of clarity. The front and back surface are covered by thermally grown oxide to act as surface passivation. The front oxide acts as a simple antireflection coating and the back oxide acts as a reflection coating.

Doping

The front emitter and contact dopings will be made using phosphorous predep with POCl3 . On the back side the top part of the pyramids will become highly doped with phosphorous and then an aluminum-silicon alloy (99%Al/1%Si) will be sputtered on. The whole structure is then submitted to a high temperature RTP step as in [6]. This step performs the final phosphorous diffusion of the front dopings and the autodoping of the back as well as acting as a gettering step.

Gettering step

In the RTP proces the final emitter and contact profiles are made. This step also diffuses the solid aluminum into the substrate to create the local back surface field. The aluminum diffuses through a large phosphorous concentration. The reason for this is to use the phosphorous for double sided gettering as well as enhancing the diffusion of aluminum. Several authors [6]-[9], have found the dual diffusion of aluminum and phosphorpous to act as an efficient means of gettering metallic impurities. As shown by *Doshi et al.* [10] high-efficiency cells can be created using RTP.

Metallization of beams

We have investigated the use of thick photoresist (AZ4562) to create a selfaligned metallization. The resist is deposited by a spin on proces. The resist becomes quite thick at the bottom of the pyramids and very thin near the edge of the beam. It has approximately the same thickness on the beams as on the edge. The resist is then exposed and developed. This means that the top layer of resist is removed and this leaves the beams clear of resist. Metal is the evaporated on to the surface. The metal on the inverted pyramids is then removed by lift-off. This proces has been tested with good results but requires further optimization.

Wafer thickness

For a pyramidal sidelength of 260µm the minimum acceptable wafer thickness is 242µm this corresponds to an average thickness of 60µm (for an octagon width of 40µm). When above this minimum thickness the increase in average thickness is proportional to the increase in wafer thickness.

CONCLUSION AND FUTURE WORK

We have described a new and effective light trapping scheme. We have shown that this scheme can be implemented with only two etching masks. It can be used with 250µm wafers to create quite thin (~70µm) cells. A proces for fabricating cells with this structure has been outlined. Dedicated masks have been developed and these will be used to fabricate cells. These masks include fourteen different cells including the structure described here with a side length of 260µm and various beam widths. It also includes perpendicular grooves of 135µm width and parallel groves (corrugated) [2] of the same widths. All the structures can be realised with two etching masks.

We expect the thin cells to have a high open circuit voltage and the effective light trapping will provide a high short circuit current. We expect highly efficient cells even on substrates with low bulk lifetime.

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